

Embedding of Optical Interconnections in Flexible Electronics

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Abstract

This paper describes the development of a flexible substrate or foil in which optical waveguides, light sources, detectors, and electronic circuitry are embedded. The generic technology offers an integrated solution to the increasing demand for flexible optical sensors and creates a technology platform for the establishment of flexible high-speed optical data connections, based on optical wave guiding layers. Patterning of the optical waveguiding is done using both a standard photolithography process and laser ablation. The resulting opto-electrical foil shows very good flexible behavior and low optical propagation and bending losses.

Introduction

Over the past 5 years the demand for flexible substrates and the applications in which these flexible printed circuit boards are being used has been constantly growing [1]. Because of their flexible behavior, the use of these substrates can significantly lower the over-all substrate thickness and weight and most of all they can ease the assembly, increase the module compactness and can be applied to a flat, a curved and even to a dynamic surface. In some applications the use of flexible substrates opens the way to roll-to-roll fabrication techniques, lowering the cost of fabrication. Most common applications are all the portable applications (mobile phone, digital camera, smart cards...).

While the electrical assembly of such flexible substrates is reaching maturity, the optical assembly is only commencing. The demand and interest for flexible optical communication is however growing for some dedicated applications, many of which triggered by the development of optical sensing techniques.

The many advantages of optical sensors make them very attractive for a wide range of applications. The immunity with regard to EMI (electromagnetic interferences), the resistance to harsh environments and the high sensitivity all make these sensors more useful than their electronic counterparts. The use of these optical sensors however always implies the use of a light-source, detectors and electronic circuitry to be coupled and integrated with these sensors. The coupling of these fibers with these light sources and detectors is a critical packaging problem and as it is well-known the costs for packaging, especially with optoelectronic components and fiber alignment issues are huge. Due to these problems optical sensing is not yet implemented in many possible and practical applications.

This research is therefore aiming at developing a generic technology that offers an integrated solution by means of developing a flexible substrate or foil in which the sensing elements can be integrated and in which also the light sources, detectors and electronic circuitry are embedded.

On the other hand, this technology platform allows the establishment of flexible high-speed optical data connections, based on optical waveguiding layers. Optical data transmission has become the obvious choice for communication over longer distances, but new trends force designers to use optical interconnections also to bridge short distances [2]. Many research institutes (including ours [3]) have proven the integration concept on a rigid printed circuit board. This paper describes the extension to flexible substrates.

Materials

Optical layers (undercladding, core and uppercladding) have been successfully deposited on rigid substrates in the past by the TFCG Microsystems-group and optical elements as waveguides, out-of-plane 45° micro-mirrors and micro-lenses were integrated [3]. These rigid circuit boards have their main applications in optical backplanes, demanding very low light propagation losses of the optical path. Bulk materials for these optical layers were chosen to have low losses at a typical wavelength of 850 nm for data communication and 1.3 or 1.55 μm for telecommunication applications. They must have the right processability properties in view of UV-crosslinking ability, spin-coating, temperature- and chemical resistance and mechanical brittleness. Special care must be taken to ensure the compatibility of the production process with the standard PCB production processes. This means the materials should be inert to production solvents and temperatures used during the production steps of the electronic assembly afterwards. The substrate should be physically and chemically stable in temperatures of about 280 degrees during solder reflows and in temperature cycling's from -40 to +85 degrees.

Truemode Backplane™ Polymer [4], Ormocer® [5] and Epocore [5] are materials which meet these requirements and have shown good results when applied on rigid substrates in the past [3]. Further material development is ongoing to create novel cross-linkable polymers with improved properties for the flexible applications.

The existing optical materials are however not flexible and strong enough to be bended without cracking or damaging. Therefore these layers are sandwiched between two spin-coated Polyimide (PI) layers, one at the top and one at the bottom, which absorb all stress and pressure during bending. PI is the dominant material in the flexible circuits industry because of its good electrical, chemical, temperature and mechanical behavior [6]. Precautionary steps had to be taken to assure the adhesion of the PI with the optical materials because of the chemical inertness of PI. Stacking of materials with such a different chemical and mechanical behavior demands special measures like CTE (Coefficient of Thermal Expansion) matching and adjusted cure-temperatures.

Best results have been obtained by using spin-coated PI[7]. The spin coat version of Polyimide is actually a polyamic acid solution. A cure heating cycle converts the acid to the insoluble imide and drives out remaining solvent. As an alternative way to fabricate the stack, the optical layers are spin-coated on a release layer and are laminated between prefabricated commercially available PI-foil after release. The optical layers can also be deposited immediately on top of a PI wafer which functions as the carrier and the final substrate at the same time [8].

Fabrication of flexible optical foil

To realise optical communication on a board, optical paths are needed to connect laserdiodes, photodetectors, optical fibers and passive optical components like splitters and multiplexers. Herefore we fabricate a stack of a cladding-layer, a core-layer and another cladding-layer. Isolating tracks in the core-layer and consequently surrounding the track completely with cladding material, results in the creation of optical waveguides. This is a well proven principle for optical interconnections on rigid boards. Light that will be coupled into these waveguides will be guided in that layer due to total internal reflection, caused by the different refractive indexes of the core- and the cladding layers.

Experiments have shown that the flexibility, strength and reliability of the complete structure is significantly improved when the optical layers are sandwiched between two Polyimide layers. Hereby we have become an almost symmetrical build-up (Fig. 1), releasing the internal stress from the central core layer. Mechanical stress caused by bending will mainly be taken up by the outer Polyimide layers, which own a high tensile strength (35 kg/mm^2) and elongation (25 %). PI is often used as a stress buffer in the semiconductor industry.

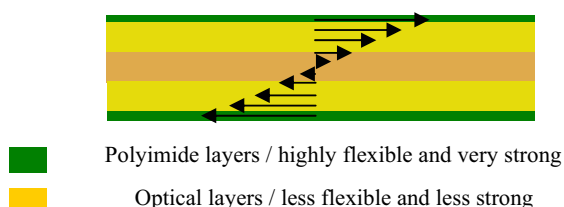


Figure 1: Symmetrical layer build-up releases the stress from the inner layers.

A crucial aspect in the process is the CTE (Coefficient of Thermal Expansion) mismatch. The industry offers a wide range of PI materials allowing us to match the CTE of the polymeric optical layers with that of the PI material [6]. Since the CTE of a layer is also influenced by the process flow of the deposition and baking, there will always exist a slight CTE mismatch. The symmetrical build-up of the stack however realizes a compensation of the CTE differences.

2*2 inch or 4*4 inch glass plates are chosen as temporary carrier. They are roughened at the upper side to avoid bad adhesion. Easy release of the substrate from this rigid glass carrier is obtained in a special way: before spinning the first polyimide layer, the 4 edges of the square glass substrate are coated with an adhesion promoter. The consequence of this is

that the first layer of polyimide adheres well to the edges of the substrates, and has marginal adhesion strength to the center of the substrate. However the adhesion to the edges is sufficient to withstand during the whole process cycle. After processing the stack can be cut out in the area of marginal adhesion by laser ablation and thus peels off easily from the rigid substrate. Laser ablation as cutting method reduces possible micro-cracks at the edges because of the local melting of the edges. The release of the carrier is performed right before the high temperature hardbake (210°C) because the low CTE of glass ($<10 \text{ ppm}$) and the high CTE of the polymers ($50\text{-}100 \text{ ppm}$) will cause fatal damage to the optical layers during hardbake.

PI is a very inert material and basically it adheres quite bad to the proposed optical materials. For this reason a plasma etch is performed on the bottom PI layer. A combination of a mixed O_2/CHF_3 (2 minutes) plasma treatment and a pure O_2 plasma treatment (for 2 minutes) results in an optimized adhesion. Before applying the top PI layer, a very thin adhesion promoter layer is spin coated and no plasma etch is needed.

The most important process parameters are the bake temperatures of the different layers. Each layer must be hardbaked at a temperature that is lower or equal than the hardbake temperature of the underlying layer. For example: to cure the top PI layer, a temperature of minimum 210°C is needed, so it is highly advisable to hardbake each layer of the structure at least at 210°C to ensure no more solvents will be driven out of the layers. Experiments have shown that, if done otherwise, the chemical structure of the top Polyimide layer can be drastically changed, loosing its strength and flexibility properties. We make use of a special low cure-temperature PI to avoid reaching the degradation temperatures of the optical materials.

A negative property of Polyimide is high moisture absorption and special care must be taken to apply a drying step after developing, cleaning or long period storage. When the stack is ready for use, a protective cover or layer should be deposited to act as a moisture barrier.

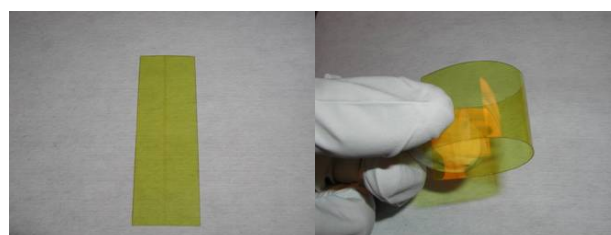


Figure 2: Epocore stack with lithography waveguides, *left*: straight *right*: bended

The proposed process layout results in a very light, thin ($160 \mu\text{m}$ total thickness) foil with a high tensile strength due to that of Polyimide. Very high flexibility is achieved and the minimum mechanical bending radius before damaging the structure is set to less than 0.5 cm (Fig. 2). The foil has been realized and the adhesion matters have been optimized for the 3 optical materials (Truemode Backplane Polymer [4], Ormocer [5] and Epocore [5]).

Fabrication of optical waveguides

Optical multimode waveguides are fabricated in two different approaches, laserablation and standard lithography. Fig. 3 shows the schematic overview of both the principles. The dimensions are chosen to be $50 \times 50 \mu\text{m}^2$ to be compatible with standard optical multimode fibers which have a typical core size of $50 \mu\text{m}$.

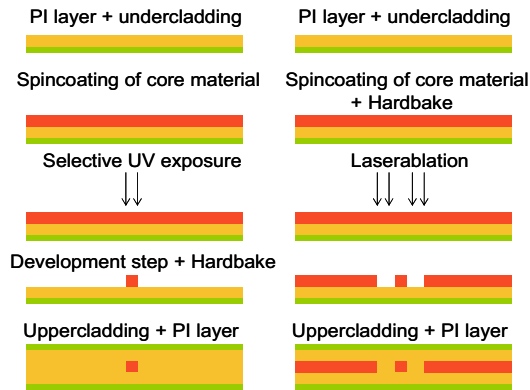


Figure 3: Schematic overview of *left*: standard lithography and *right*: Laser ablation

Laser ablation can be described as a micromachining technology that is based on the controlled removal of material with intense laser pulses. Depending on the wavelength and the material, this can have the characteristics of ablative photodecomposition, or rapid heating and vaporization. KrF Excimer laser ablation (wavelength 248 nm) is particularly well suited for structuring of polymers because of their excellent UV-absorption properties and highly non-thermal ablation behavior. The substrate is positioned on a $30 \times 30 \text{ cm}$ high accuracy translation stage ($1 \mu\text{m}$ motion resolution). Sample motion and beam handling is fully computer controlled. A scanning electron microscope (SEM) image of a single waveguide fabricated using KrF Excimer laser ablation is shown in Fig. 4, an array of 10 waveguides in a full stack is shown in Fig. 6. The picture shows the structured core layer prior to application of the upper cladding layer. Optimization of the ablation parameters is required in order to achieve the very smooth sidewalls and the absence of debris.

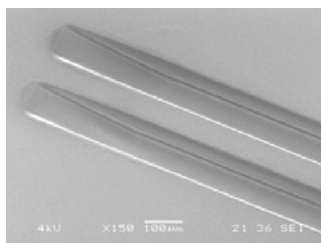


Figure 4: SEM picture of a laser ablated waveguide in Truemode Backplane Polymer

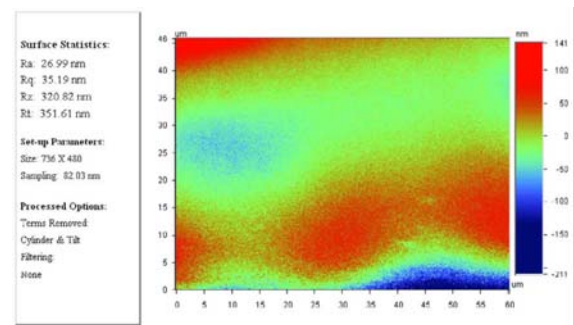


Figure 5: Wyko plot of a laser ablated vertical sidewall, showing 27-nm Ra roughness and 35-nm rms roughness, measured on an area of $60 \times 46 \mu\text{m}^2$.

This results in the smoothness of a laser ablated sidewall of 27-nm Ra and 35-nm root mean square (rms) roughness (cylinder and tilt removed), measured on an area of $60 \times 46 \mu\text{m}$ for a Truemode Backplane Polymer waveguide (Fig.5). Laser ablation ofOrmocer and Epocore generates too much debris (laser ablated particles resettling on the surface) and the roughness of the sidewalls is too high, which will result in high light propagation losses.

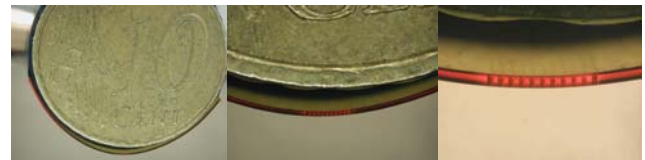


Figure 6: Complete stack with laser ablated waveguides in Truemode Backplane Polymer, over a coin with radius of curvature of 1 cm.

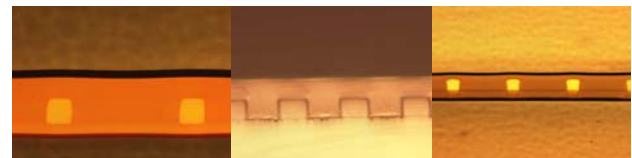


Figure 7: Complete stack with photolithographic waveguides in *left*: Ormocer, *middle*: Epocore (on FR4-material) and *right*: Truemode

For Ormocer and Epocore [5], well defined waveguides can be fabricated with a standard lithography step. The material acts as a negative resist. Areas of the core layers which are exposed to the UV source will cross-link while the unexposed areas remain soluble in a developer solution. Very sharp edges and smooth sidewalls can be obtained with this technique. Ormocer material however is still sticky after the prebake step, so any contact with the mask must be avoided to avoid contamination. UV-exposure in proximity mode demands for a highly controllable height between substrate and mask and results in less sharp, but acceptable edges of the waveguide (Fig. 7). Experiments have pointed out that for Ormocer®, the adhesion of the waveguides to the cladding layer depends on the UV exposure time. Best adhesion is obtained at the longest exposure times. After the developing

of the non-exposed areas, the waveguides are all that is left from the core layer, so the top cladding layer must have twice the thickness of the waveguides to obtain a symmetrical build-up.

The resulting waveguides have low propagation losses lower than 0.15 dB per cm and bending losses lower than 0.15 dB per cm for a bending radius of 15 mm and lower than 0.25 dB per cm for a 8 mm bending radius for Truemode Backplane Polymer. Fig. 8 shows the optical measurement set-up: A controlled Laserdiode emits 850 nm wavelength light into a glass fiber. The other end of this fiber is actively aligned with one end of the waveguides. When the light has propagated through the waveguide, it is coupled out into an actively aligned glass fiber which leads towards a photodiode. This way the propagation and coupling losses can be measured using the cut back method. The waveguides can now be bended as we wish. The extra power loss measured is the bending loss. Fig. 9 shows the propagation-, coupling- and bending losses for 10 waveguides with a length of 8 cm. The waveguides were bended in the set-up that is shown next to the graph.

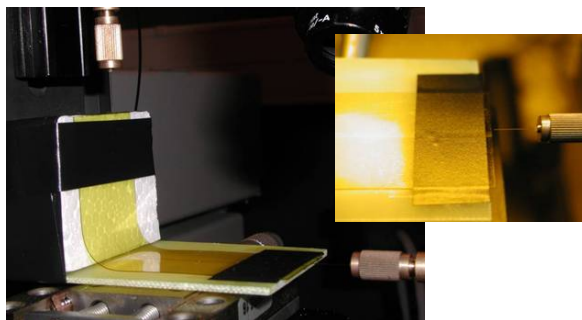


Figure 8: Optical loss measurement set-up

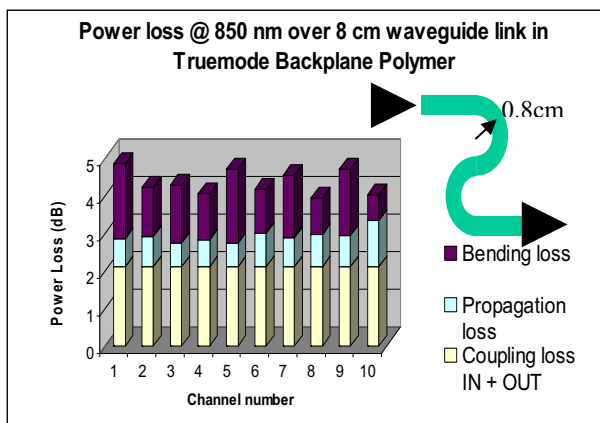


Figure 9: Propagation-, coupling- and bending losses

Fabrication of 45 degrees out of plane turning mirror

The data-carrying light can be vertically coupled in- and out of the waveguides with 45 degrees out of plane deflecting micro-mirrors, terminating the waveguides and connecting them with laser diodes, receivers, optical fibers, open air or optical elements. Two basic fabrication methods are proposed and shown in Fig. 10.

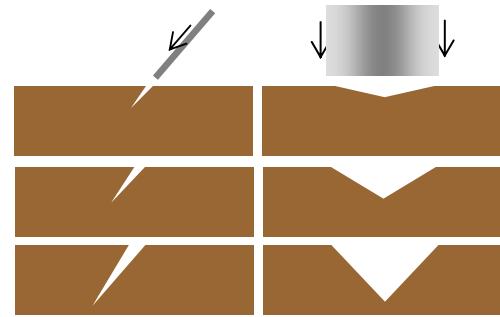


Figure 10: Schematic overview of the fabrication of micro-mirrors: *left* tilted laserbeam ablation ; *right* vertical distributed laser ablation

By tilting the beam delivery optics of the Excimer KrF laser setup the laser beam impacts on the surfaces with a tilt of 45°. This results in a tilted laser ablated cavity (Fig. 11). Deposition of a metallization layer on the sidewall of this cavity creates a 45° reflecting mirror. Later on the cavity is filled with the cladding material while ultrasonic treatment avoids air bubbles captured in the cavity. It can be seen that using the Excimer laser, there is always a certain tapering of the edges. The tapering effect is shown to be highly reproducible; therefore this effect can be compensated for, in order to achieve an angle of 45° at the positive facet.

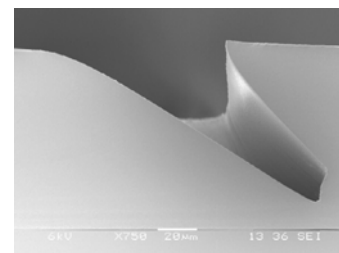


Figure 11: Micro-mirror in Truemode Backplane Polymer, using the tilted laserbeam

The second fabrication approach consists of a distributed exposure of the surface to the laser beam. The sample is moved horizontally while a triangular shaped laser beam is ablating the surface. This way a smooth V-groove with 45° edges is ablated in the surface. Fig. 12 shows a Scanning Electron Microscope picture of such a mirror structure.

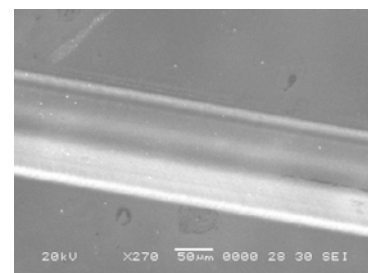


Figure 12: SEM picture of a micro-mirror in Truemode Backplane Polymer, using the distributed laser ablation technique.

After metallization, this structure acts as a mirror. The advantages of this second method is the absence of a negative facet (no air bubbles can be trapped in the cavity), the ease of alignment (the beam impacts vertically on the substrate) and a better depth control (important when mirror has to be ablated on top of an active component). The depth of the V-groove and thus also the mirror angle can be fine-tuned by controlling the laser power, see Fig. 13.

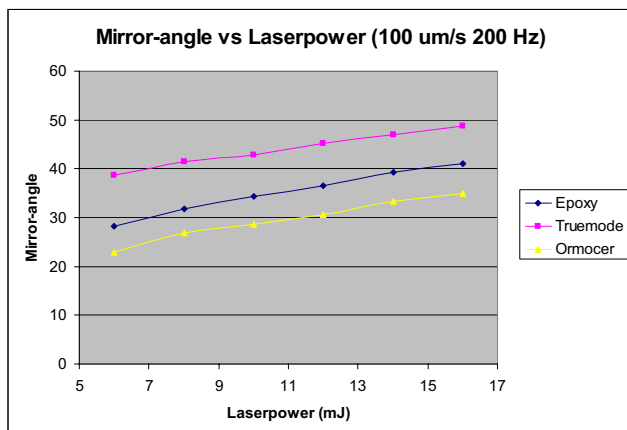


Figure 13: Mirror-angle dependency of the laser power for a translation speed of 100 µm/s and a pulse frequency of 200 Hz.

The smoothness of a laser ablated sidewall of such a V-groove is 85-nm Ra and 111-nm root mean square (rms) roughness (cylinder and tilt removed), measured on an area of 90x50 µm for Truemode Backplane Polymer (Fig.5). Ongoing fine-tuning of the other laser parameters shows promising results to lower down these roughness values.

Embedding of active optoelectronic devices

This research aims for a generic technology that offers an integrated compact solution for optical communication in foil. Integrating active components in the foil is therefore essential to reach fully embedded optical links. VCSEL's and Photodiodes have been embedded in optical layers before, to implement them onto rigid boards [9], but not yet to form an autonomous opto-electrical foil.

The optical active components need electrical IC's as drivers or amplifiers. Earlier research at our department resulted in a technology for an Ultra-Thin Chip Package (UTCP) [10], based on the embedding of ultra-thin dies in flexible substrates. Chips with thickness in the range of 20-30 µm are packaged in between 2 polyimide layers. This results in a very thin chip package, with a total thickness of only 50 - 60 µm (Fig. 14). Chip, PI layers and metal are so thin that the whole package is bendable. This method of embedding is extended for the optical foil, see Fig. 15. The VCSEL's and Photodiodes and electrical IC's will be thinned down by lapping and polishing to reach a thickness of about 40 µm. These thin chips are embedded in a cavity in the first cladding layer. When standard lithography is used to outline the cavities, problems occur during the development step. The adhesion of the optical polymers with the underlying PI layer

before hardbake seems to be too bad, so the development solution creates disadhesion of the two layers in the region of the cavity.

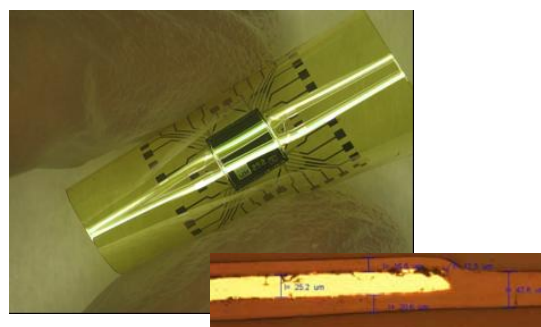


Figure 14: UTCP- Ultra Thin Chip Package [10].

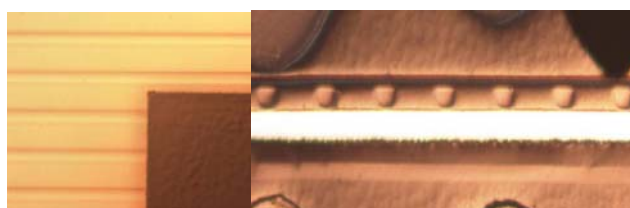


Figure 15: 30 µm thick copper samples, used as dummy chip, embedded in the cladding layer of the optical foil. Waveguides can be seen on top of the embedded sample.

A well proven alternative is laserablation with the KrF Excimer laser (wavelength 248 nm). To ensure a good depth control, a copperstop is applied to the PI layer. This copperstop consist of a local sputtered layer of TiW (50 nm) for adhesion promotion and a sputtered and electroplated copper (9 µm). During laserablation, all the polymer material is removed selectively from the cavity while the copper layer is not ablated and becomes the bottom of the cavity (Fig. 16).



Figure 16: Laser ablated cavity for VCSEL array embedding; dimension: 3000 * 280 µm²

After cleaning of the substrate, an adhesive is deposited into the cavity. Underfill adhesives for flip chip bonding with very low viscosity and low thermal cure-temperatures have shown good results for this application. The thin dies are then placed manually into the cavity. Optimised dimensions of the cavity can result in alignment errors < 15 µm (Fig. 17). This is not sufficient for optical coupling, but the real fine alignment happens later. A thermode levels the die in the cavity and cures the underfill adhesive.

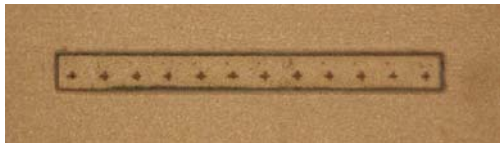


Figure 17: Dummy VCSEL array embedded in a laser ablated cavity using underfill material as adhesive.

In a next step, the core layer is spin coated on top of this structure. The fabrication of waveguides in the core layer is described earlier. As well for the laser ablated waveguides as for the lithography waveguides, alignment of $<5 \mu\text{m}$ in relation to the active areas of the optical active dies, can be achieved after optimization (Fig. 18). Same accuracy is realised for the laser ablated micro-mirrors which are fabricated afterwards. The $5 \mu\text{m}$ precision is crucial for the feasibility of a low loss optical connection [11].

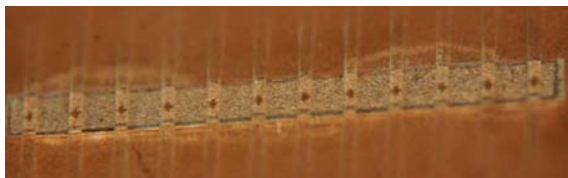


Figure 18: Epocore waveguides on top of an embedded VCSEL dummy. Alignment of the waveguides has been done through the help of laser ablated marks on the copper dummy

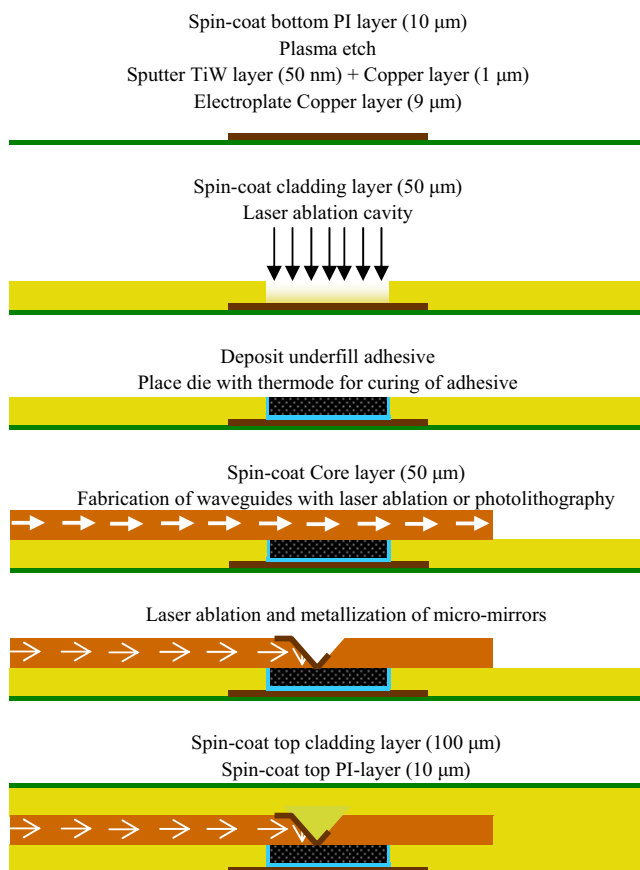


Figure 19: Process flow for the production of an optical foil with embedded active opto-electronic components

Alignment and process issues were optimized for mechanical chips. An overview of the process flow can be seen in Fig. 19. Pictures of the resulting optical foil are in Fig. 20. Ongoing research aims at the characterisation of functional optical links with functional VCSEL's and PD's. As an alternative to thinned-down dies, standard components with $150 \mu\text{m}$ thickness can be embedded by using a $150 \mu\text{m}$ thick cladding layer or multiple $50 \mu\text{m}$ layers. Optimisation of the adjusted process flow has been done. Using thicker chips than $50 \mu\text{m}$ is however a draw-back for the flexible behaviour of the optical foil.

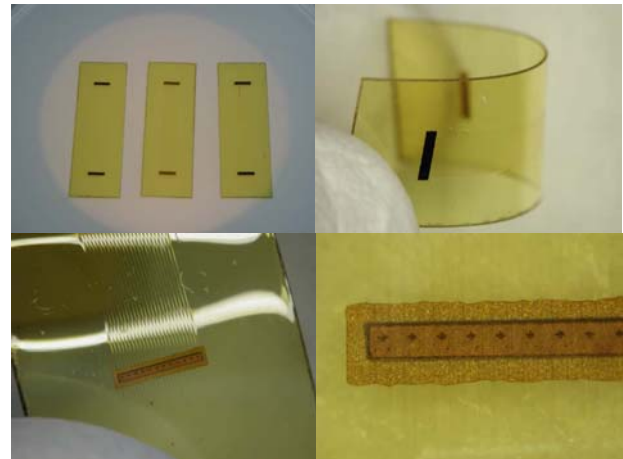


Figure 20: Pictures of the optical foil with embedded dummy VCSEL array's, waveguides and micro-mirror's.

Electrical assembly of the substrate

All active components should be electrically connected to each other. Micro-via's are ablated using a frequency tripled Nd:YAG laser (355 nm wavelength) and metallized by sputtering and plating to fan out the contacts on the top PI layer where all other electrical assembly can be done with standard flex assembly processes. The optical layers have proven to withstand the temperature cycles during these procedures. The optical components have been chosen to have all electrical pads at the top side to simplify the assembly to one sided flex technology. However double-sided routing of the electrical connections is well known nowadays and could be perfectly done in this application because of the symmetrical build-up.

In ongoing research, a combination of all the above techniques will be united in a proof-of-principle demonstrator. This consists of a thin foil ($160 \mu\text{m}$) with completely embedded optical data channels between embedded functional active opto-electronic components which are triggered by fully embedded electrical IC's. As an alternative, the same module can electrically process the optical signals of an external, mounted or embedded optical fiber sensor.

Conclusion

The increasing need for flexible modules and the integration of photonics on printed circuit board's results in a challenging and competitive research which combines both

needs by embedding passive optical interconnections and active optoelectronic devices on flexible Polyimide substrates, resulting in a complete autonomous opto-electrical and flexible module. Dummy electrical and opto-electrical dies were successfully embedded in the foil. Low loss waveguides, micro-mirrors and micro-via's were fabricated using laser ablation and standard lithography and aligned with the dies, meeting the application requirements. The resulting opto-electrical foil has a thickness of about 160µm and shows high flexibility. Materials are chosen to be compatible with standard flex and PCB fabrication technologies.

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